Appendix C

In-situ Coal Gasification

A Final Phase IV Report

Prepared by CCPC Technical Committee, April 2014

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Figures and Tables

In-situ Coal Gasification

1. Background

In-situ coal gasification (ISCG) is an emerging, transformational clean energy technology with tremendous potential to support a long term sustainable Alberta economy by unlocking significant deep coal resources. ISCG is a method to extract energy from deep, currently unmineable coal seams. Oxygen (or air) and steam are injected into a coal seam through an injection well. The oxidants react with the coal in-situ through a set of pyrolysis, gasification and oxidation reactions to produce synthesis gas (syngas) comprising primarily CH_4, CO, H_2, CO_2 and trace gases such as H_2S. Syngas, which is brought to the surface through a production well, can be used to produce a range of products including power and liquid fuels.

2. Objective

The objective of this study was to provide sufficient background information on in-situ coal gasification to a group of diverse stakeholders to set the foundation for the development of an industry/government consortium leading to ISCG field demonstration pilot test work to support commercialization. Carbon Development Partnership, Alberta Innovates – Energy and Environment Solutions and the Canadian Clean Power Coalition have jointly funded this study. The study focused on the technical requirements and economic merits of employing ISCG derived syngas for use in a Once Through Heat Recovery Steam Generator (OTSG), a Fischer-Tropsch (FT) liquids plant and a combined cycle power plant. The focus of this report is on the results for the combined cycle power plant.

A future demonstration pilot test (outside the scope of this study) would:

- Use the most promising ISCG technology for the selected site
- Study syngas use
- Provide adequate field data to evaluate the value proposition and associated costs
- Demonstrate greenhouse gas reduction opportunities
- Support policy development
- Lead, ultimately, to several commercial ISCG operations in Alberta

The study had the following broad objectives:

- Technical: To accelerate the deployment of ISCG technology in Alberta. Screening level data was compiled to educate participants on the key operational attributes, technology options and risks associated with ISCG technology.

- Economic: To use the technical data generated to evaluate the value proposition and business case for the ISCG technology for selected Alberta coal seams.

- Pathway to Commercialization: To identify follow-up activities to support the development of an industry/ government consortium leading to ISCG field demonstration pilot test work and ultimately, commercialization.

The information generated could be used as part of an overall package to demonstrate the importance of developing Alberta's deep coal resources. However, the development of a demonstration pilot plant is outside the scope of this study.

3. Scope of Study

The overall work completed for this study is described below.

Technical

- ISCG Technology Comparison: An evaluation of the most promising ISCG technologies (Parallel-CRIP [controlled retraction of the injection point], Linear CRIP and linked vertical wells [or a combination thereof]).

- Technical/Operational Challenges: A brief review of the operational and technical challenges that may have historically limited the widespread commercial adaptation of the ISCG technology.

- Enabling Technologies: A review of recent advances in key technologies (e.g. horizontal drilling) that may enable the cost effective commercialization of ISCG technologies.

- **Complementary Technologies:** A high level comparison with partial combustion based bitumen extraction technology and steam assisted gravity drainage (SAGD) operations.

- **Drilling Costs:** To the extent possible, indicative costs associated with in-situ drilling requirements for each technology option and indicative cost savings from optimizing the scale-up from single modules to multiple modules for each technology were reviewed.

- **Computer Modelling of ISCG:** A review of applicable ISCG modelling techniques and a preliminary performance comparison between ISCG technologies to the extent possible.

Environmental

- **Environmental Monitoring Requirements:** A high level review of environmental and process monitoring requirements for selected coal seams.

- **Review of Environmental Factors:**

  - **GHG Footprint:** A proof of concept level evaluation of the greenhouse gas (GHG) reduction options from ISCG relative to regulatory requirements to reduce GHG.

  - **Groundwater:** The considerations required in the plant design to avoid groundwater problems were addressed.

  - **Ground Subsidence:** The considerations required in the plant design to avoid surface subsidence problems were addressed.

Economics

- **Expected CAPEX/OPEX Reductions:** Screening level engineering studies were completed to further quantify the Alberta-specific value proposition for ISCG syngas to selected final products. A comparison of the expected reduction in capital expenditures/ operating expenditures (CAPEX/OPEX) and economics for the use of ISCG technology compared to the current/expected reference (base) cases for each end product identified below (power, FT-liquids, SAGD steam) was conducted.

Regulatory/Permitting

- **Roadmap for Environmental/Regulatory Permitting:** An overview of the environmental and regulatory permitting requirements in the province of Alberta, based on a review of the applications for ISCG pilot plants recently approved under the experimental provisions by the province. Determined the environmental and regulatory permitting requirements for both a field demonstration facility and an eventual commercial facility.

Commercialization

- **Roadmap for Commercialization:** A high level road map and progressive activity list were developed for a stage-gate pathway towards the commercial application of ISCG in Alberta.

4. Study Overview

4.1. Technology Consideration

In the in-situ coal gasification (ISCG) process, oxygen (or air) and steam are injected into a deep coal seam through an injection well. The oxidants react with the coal in-situ through a set of pyrolysis, gasification and oxidation reactions to produce synthesis gas (syngas) comprising primarily of CH_4, CO, H_2, CO_2 and trace gases such as H_2S. Syngas, which is brought to the surface through a production well, can be used to produce a range of products including power, boilers, transportation fuels and petrochemicals.

The technical and economic value proposition of ISCG technology for deep Alberta coal seams is evaluated in this report.

Key Findings

- Alberta has vast quantities of geologically continuous, currently unmineable deep coal resources that could potentially be recovered through in-situ coal gasification (1.5 trillion tonnes at depths of 250 to 3,600 m and with seam thicknesses of up to 12 m to support multiple commercial scale operations).

- The well drilling and completions technologies required for in-situ coal gasification are relatively well established and commercially proven for in-situ bitumen extraction from the oil sands, and could be readily adapted.

- The marginal cost of syngas production from an integrated ISCG/FT liquids facility can be significantly lower than the current price of natural gas due to the high level of integration with the oxygen supply and ISCG process requirements.

- Once constructed, an ISCG syngas plant could become a predictable, cost stable, low-cost supplier of energy for a base load fuel or syngas processing application for:

    - The production of FT transportation fuels, essentially eliminating the natural gas price volatility impact on the economics of a conventional gas to liquids plant; power generation while meeting new federal regulations on greenhouse gas emissions from coal based power plants and cost competitive with natural gas-fired combined cycles operating as base load units (95 per cent capacity utilization) at projected natural gas prices.

    - Use as a boiler fuel for steam assisted gravity drainage operations, replacing natural gas. The analysis indicates that there would be essentially no change to the boiler performance due to the fuel switch to syngas and minimal retrofit costs. In addition, a 10 to 15 per cent reduction in the greenhouse gas intensity (tonne of CO_2 per barrel produced) for bitumen production could be achieved compared to using natural gas a fuel.

- Surface processing facilities to treat the syngas are based on commercially proven processes.

- Environmental and regulatory permits for an ISCG facility can be obtained; the Alberta regulatory regime is one of the most advanced jurisdictions in the world with respect to ISCG permitting.

The study finds that the ISCG technology and economics look promising. However the analysis assumes a long term, consistent syngas quality and quantity, which must be confirmed through site specific field demonstration. A key limitation of the study is the reliance on computer simulations, using design conditions significantly beyond existing operating experience, such as:

- Deeper coal seams (> 200 m depth); and

- Continuous operation at greater commercial scale syngas production rates.

It is therefore recommended that commercialization of the technology in Alberta be preceded by field demonstration of ISCG technology by a consortium of interested parties to generate the required performance and scale-up data to support commercialization, including:

- Investigating a strategy for commercialization of the ISCG technology as initially a complementary, not primary, feedstock source for an existing or new commercial scale facility where the syngas production can be gradually incorporated into commercially proven operations.

- Finalizing a strategy for field demonstration that stages promising ISCG Technologies, capital outlay, minimizes scale-up risk and maximizes scale-up data generation and results in an optimized ISCG Module configuration for a specific site.

- Conducting targeted screening level technical and regulatory work to define the requirements for a site-specific, scale-up and commercialization focused field demonstration of ISCG technology in Alberta.

- Developing a better understanding of ISCG technology through controlled laboratory physical test work coupled with advanced computer modelling.

4.2. Coal Resources in Alberta

Alberta's coal resources, at depths greater than 150 m, are estimated by the Alberta Geological Survey to be in excess of two trillion tonnes, while the surface coal resource is estimated to be 33 billion tonnes. The energy value in these resources is greater than the energy value of all of Alberta's oil and gas resources combined, including the oil sands. The major coal zones of the plains area of Alberta are the Ardley coal zone, the Drumheller coal zone, and the Mannville coal zone; the estimated tonnage in place is summarized in Table 1 (based on publicly available data from over 350,000 oil and gas boreholes that have been drilled historically, and 15,000 to 20,000 boreholes that are added to the database annually).

Table 1: Summary of Major Alberta Coal Zones

Coal Zones	Area (km²)	Coal (Gt*)	Depth Range (m)	Seam Thickness
Ardley	59 000	596	0 - 1 000	up to 10 m
Drumheller	128 000	564	0 - 1 300	up to 5 m
Mannville	253 000	500	250 - 3 600	up to 12 m

* *Gt (gigatonnes or billion tonnes)*

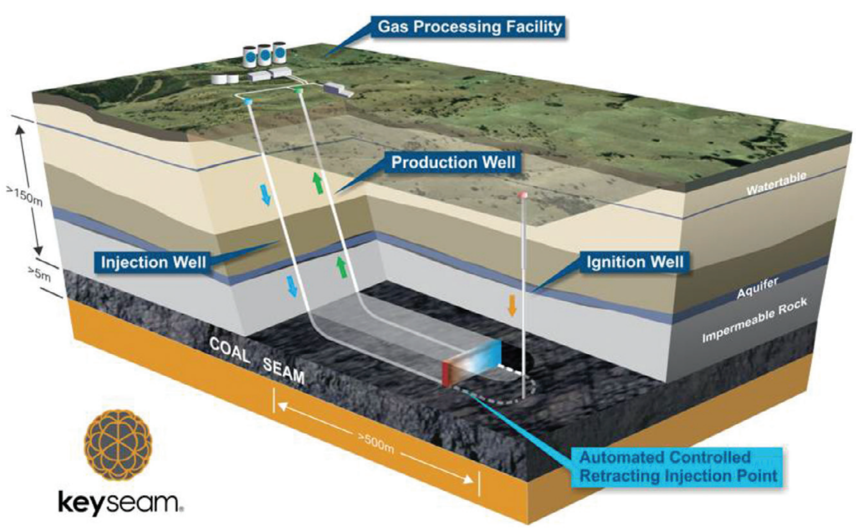
5. In-situ Coal Gasification Technology Options

Alberta has the diverse technical know-how to commercialize ISCG technology because of significant expertise in drilling and completions technology, chemical processing, carbon capture and the extensive conventional and unconventional oil and gas industry in the province. Three ISCG technologies evaluated for this study are described next.

5.1. Parallel-CRIP Technology

In the Parallel-CRIP (Controlled Retraction of the Injection Point) module shown in Figure 1, two process wells (injection and production wells) are drilled in-seam parallel to each other. The two wells are deviated towards each other at the end of the in-seam section (horizontal reach) and converged towards a third vertical borehole that is used to ignite the surrounding coal. Once the coal is ignited, the ignition point is continually retracted as the coal continues to gasify. Multiple modules operating simultaneously would be expected to generate the syngas required for a commercial scale operation.

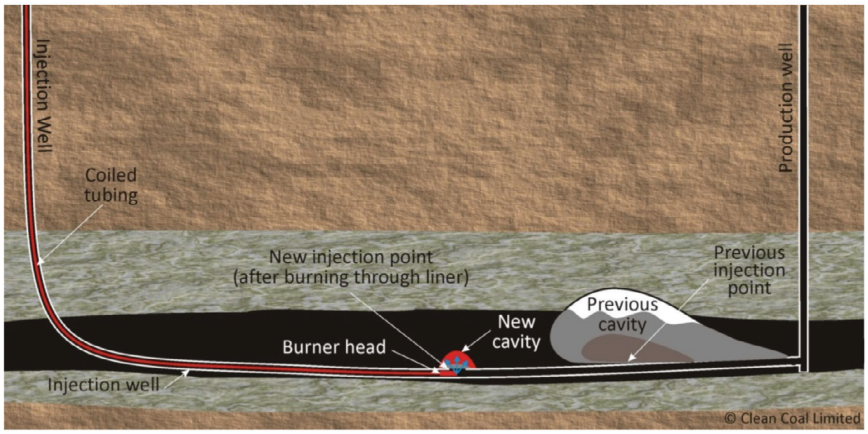
Figure 1: Schematic of the Parallel-CRIP Configuration Showing the Location of the Process Points (Graphic Courtesy of Carbon Energy Limited)



5.2. Linear-CRIP Technology

The Linear-CRIP Module comprises a deviated in-seam injection linked to a vertical production well as shown in Figure 2. Coal ignition around the injection point gasifies the surrounding coal to the point in time where the quality and quantity of the syngas is not acceptable. The injection point is then retracted into fresh coal and re-ignited.

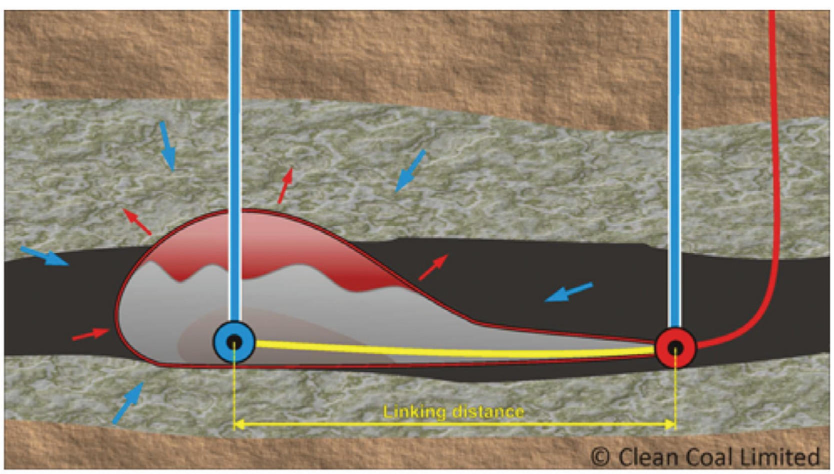
Figure 2: CRIP Maneuvers and New Reaction Zone Ignition in Linear-CRIP



5.3. Enhanced Linked Vertical Well (Enhanced-LVW) Technology

In this technology, modules comprise at least two vertical wells per panel (Figure 3). Linkage between the wells is achieved by enhancing permeability of the seam by additional means such as coiled tube or horizontal drilling. The exact configuration of wells required to extract energy from a panel is considered proprietary.

Figure 3: The Enhanced-LVW Configuration



6. Power Generation from ISCG Syngas

This section summarizes the operational performance, capital and operating costs and economics for a plant to generate power from syngas produced from an in-situ coal gasification (ISCG) facility in Alberta, Canada. The potential cases of interest are based on the choice of oxidant for the ISCG process and the required level of CO_2 capture:

- Air blown vs. oxygen (95 mol% or 99.5 mol%) blown in-situ gasification
- Sufficient CO_2 capture to meet Canadian federal regulations for CO_2 emissions intensity for coal fired power generation (0.42 tonne/MWh)

6.1. Air vs Oxygen and Oxidant for Syngas Production

The bulk of the parasitic power loads at the power generation facility to supply oxidant vary depending on the coal seam depth. These parasitic power loads consist of:

- The air separation unit (for oxygen blown ISCG) including oxygen compression
- Air compressors (for air blown ISCG)
- Diluent nitrogen compressors (if required)
- Syngas compressor (for shallow seams <500 m) and syngas expander (for deep seams >600 m)
- Auxiliary power loads

All other power loads at the power generation facility are expected to be essentially constant and do not impact this analysis. A thorough analysis was completed comparing the costs of operating with air rather than oxygen. It was determined that oxygen works best the greater the depth of the seam, and deeper seams have better economics. Therefore, a decision was made to incorporate the use of oxygen into the cases studied.

6.2. Base Cases

The two base cases for comparative purposes were prepared:

- **Base Case (Base-1):** Current state of the art 500 MW Gasifier IGCC (Case 1) based on surface mined coal and surface gasification technologies.
- **Base Case (Base-2):** A base loaded natural gas combined cycle (NGCC) 2 X 1 F-Class power plant.

In consultation with the Study Group, the following unit operations were pre-selected for Base-1 to allow comparison to previous studies conducted: acid gas removal (AGR) (Selexol®), sulphur recovery unit (SRU) (Claus) and Gas Turbine (F-Class Syngas) technologies for syngas processing.

6.3. Study Case

The target CO_2 emissions intensity for the partial capture cases is 0.420 tonne CO_2/MWh as stipulated by new Canadian federal regulations for coal fired power generation facilities. Sufficient cost data for the partial capture Case P2 was provided to allow the cost estimate for the other complementary case (Case P1) to be approximated through elimination of major processing blocks. None of the air blown ISCG cases (Case P4, P5 and P6) were evaluated based on the initial assessment of air fired vs. oxygen fired ISCG plant. A linear CRIP configuration was used for the economic analysis.

7. Key Performance Metrics

The major operating metrics calculated in the study are summarized in Table 2.

Table 2: Summary of Major Performance Metrics

				Pulverized Coal Power	
	ISCG (Case # P2)	IGCC Part CCS	Base-2 (NGCC)	No CO_2 Capture	With CO_2 Capture
Net Power Generation (MW)	492	483	535	450	360
Design Life (Years)	30	30	30	35	35
Average Capacity Factor (%)	95	85	50	93	90
Available Pre-combustion Carbon Captured (%)	50.6	53	0	0	~53
GHG Intensity (tonne/MWh)	0.42	0.44	0.35	0.90	0.42
Heat Rate (GJ/MWh)	7.1	10.2	7.1	9.6	12.8

In all CO_2 capture cases, CO_2 is dried and compressed and sent to the battery limit. No transportation or sequestration costs are included in the analysis.

Capital intensities show that an ISCG plant could reduce the required capital expenditures by 60 per cent from IGCC and almost 40 per cent from a pulverized coal plant with CO_2 capture, but would still cost more than twice as much as NGCC.

8. Greenhouse Gas Emissions

Table 3 shows CO_2 emissions for each case studied. The carbon content that exists within methane was not captured and hence ends up as CO_2 emissions from the power generation facility, for both the ISCG and NGCC cases.

Table 3: Comparison of CO_2 Emissions for Different Study Cases

	Base Case-1	Case P2	Base Case-2
	IGCC (Full Capture)	O_2 Blown ISCG (Partial Capture)	NGCC (No Capture)
% Carbon Capture	93.2	50.6	N/A
Carbon Intensity (Kg/MWh)	75	420	353

9. Economic Results

9.1. First Year Cost for Power

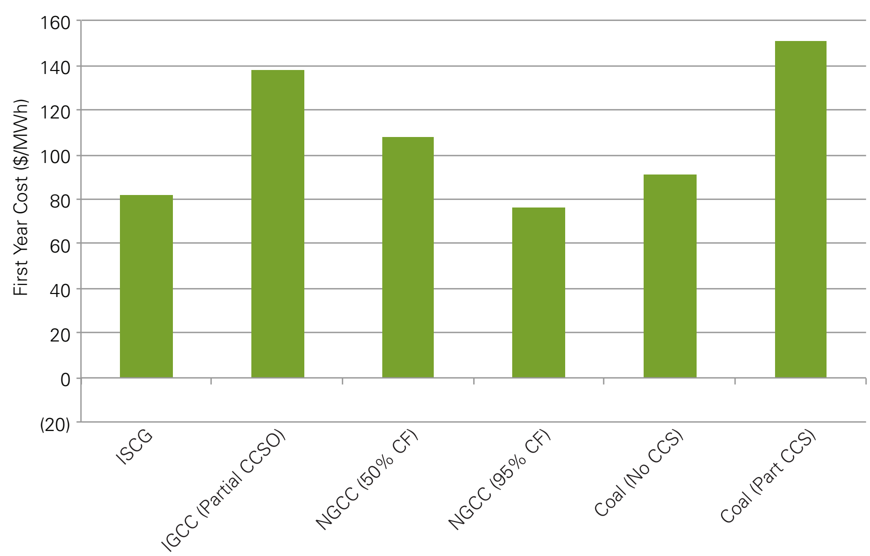
The ISCG case for power generation has been designed to capture enough CO_2 to meet the new Canadian federal regulations stipulating an emission limit of 0.42 tonne CO_2/MWh for coal based power generation facilities. Compression costs for the captured CO_2 are included for all ISCG cases. There is a significant methane content in the ISCG syngas, and thus while 89 per cent of the CO_2 in the syngas is captured prior to combustion, this corresponds to only 51 per cent carbon capture prior to combustion. The CAPEX intensity for the ISCG syngas case is nearly 60 per cent lower than for the surface gasifier based combined cycle power generation unit; the ISCG syngas CAPEX is nearly 40 per cent lower than a pulverized coal power plant with post combustion CO_2 capture. Approximately 50 per cent of the ISCG syngas CAPEX is required for raw syngas clean-up, processing and CO_2 capture and compression.

The first year cost of power is derived by setting the price for power in the first year escalated by 2 per cent in following years such that the net present value of the project equals zero. The required first year selling price for power for the ISCG syngas case is approximately one-third of the price required for a similar IGCC facility. This is comparable to that required for a traditional pulverized coal power plant, and significantly lower than for a pulverized coal power plant retrofitted with carbon capture technology at a similar capture level.

The first year price of power required for an NGCC unit is very sensitive to changes in the price of natural gas (high commodity price risk). On the other hand, ISCG syngas will provide the power producer a stable cost for fuel over the long term.

Figure 4 illustrates the comparison of the required first selling price (2016) of power required to achieve an after-tax un-levered internal rate of return (IRR) of 9 per cent for the six comparative cases.

Figure 4: First Year Cost of Power (2016)



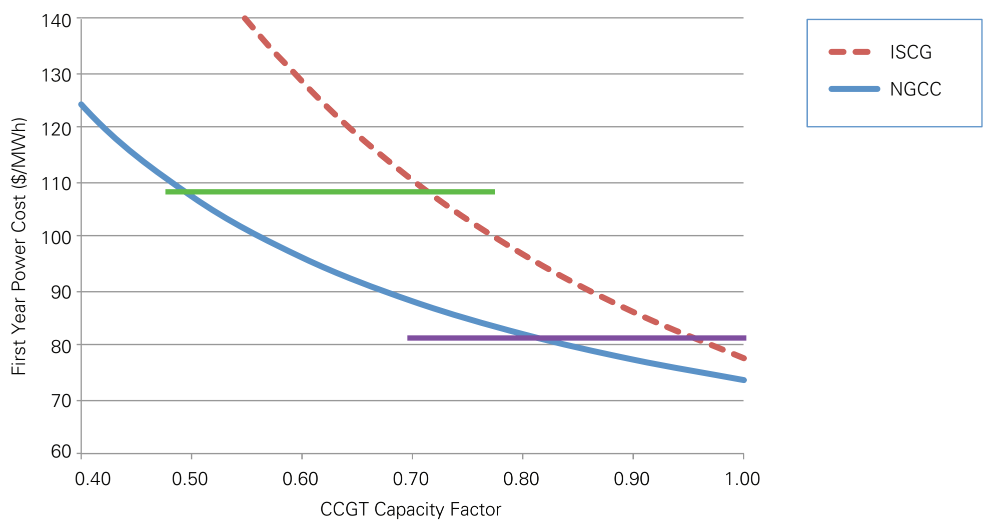
Note from Figure 4:

- An NGCC plant with a 95 per cent capacity factor has a slightly lower first year cost of power than the ISCG plant. This means that for the same all hour power price, the NGCC unit operating at 95 per cent capacity factor would have a higher IRR than the ISCG plant. Given the relatively high marginal cost of the NGCC unit, it will likely only run roughly 50 per cent of the time. The ISCG plant will have a very low marginal cost and will therefore run most of the time.
- The required first year selling price for power for the ISCG case is comparable to that required for a traditional pulverized coal power plant, and significantly lower than for a pulverized coal power plant that deploys post-combustion carbon capture technology with a similar CO_2 emission intensity (0.42 tonne CO_2/MWh).
- The required first year selling price for power for ISCG is approximately one third of the price required for a comparable IGCC facility ($82/MWh compared to $247/MWh).

9.2. Capacity Factor Sensitivity

Figure 5 shows a comparison between the first year cost of power for the ISCG and NGCC cases as the capacity factor of the plant changes. The NGCC case would have to operate with a capacity factor of about 80 per cent (purple line) to have a similar first year cost as the base loaded ISCG case operating at a 95 per cent capacity factor. The capacity factor of the ISCG case would have to be reduced to about 70 per cent (green line) to match the first year cost of the NGCC case operating at a peak loaded capacity factor of 50 per cent. However, given that the NGCC case is expected to run only during higher priced periods, it is not clear whether the NGCC or the ISCG unit will be more profitable at the applicable forecasted power prices.

Figure 5: Impact of Capacity Factor on Required First Year Cost of Power



10. Environmental and Regulatory Permitting of ISCG

Permits for an ISCG facility can be obtained; the Alberta regulatory regime with respect to ISCG is more advanced than most jurisdictions in the world. The regulatory process is well laid out for the orderly development of energy related resources, including for ISCG technology demonstration and commercialization. The potential environmental impacts of ISCG are well known and technology exists to mitigate potential issues:

- Proper site selection is the most important mitigating factor for environmental effects
- Surface subsidence is mitigated by appropriate site selection
- Surface and groundwater protection is achievable through proper site selection, monitoring, and control of in-situ gasification operations

11. Conclusions

In the in-situ coal gasification (ISCG) process, oxygen (or air) and steam are injected into a deep coal seam through an injection well. The oxidants react with the coal in-situ through a set of pyrolysis, gasification and oxidation reactions to produce synthesis gas (syngas) comprising primarily of CH_4, CO, H_2, CO_2 and trace gases such as H_2S. Syngas, which is brought to the surface through a production well, can be used to produce a range of products including power, transportation fuels and petrochemicals.

The technical and economic value proposition of ISCG for deep Alberta coal seams is evaluated in this report. Key findings include:

- Alberta has vast quantities of geologically continuous, currently unmineable deep coal resources that could potentially be recovered through in-situ coal gasification (1.5 trillion tonnes at depths of 250 to 3,600 m and with seam thicknesses of up to 12 m to support multiple commercial scale operations).

- The well drilling and completions technologies required for in-situ coal gasification are essentially all well established and commercially proven for in-situ bitumen extraction, and could be readily adapted.

- The marginal cost of syngas production from a stand-alone ISCG facility is significantly lower than the current or projected price of natural gas. Once constructed, a facility using ISCG syngas would switch back to natural gas only if prices dropped below this marginal cost. The marginal cost of syngas production from an integrated ISCG/FT liquids facility can be significantly lower than ISCG for power due to the significant potential for integration between the ISCG syngas production facility and the FT liquids facility.

- An ISCG syngas plant, once constructed, could become a predictable, stable, low-cost supplier of energy for a base load fuel or syngas processing application for power generation while meeting new federal regulations on greenhouse gas emissions from coal based power plants and cost competitive with natural gas fired combined cycles operating as base load units (95 per cent capacity utilization) at projected natural gas prices.

- Surface processing facilities to treat the syngas are based on commercially proven processes.

- Environmental and regulatory permits for an ISCG facility can be obtained; the Alberta regulatory regime is one of the most advanced jurisdictions in the world with respect to ISCG permitting.

12. Recommendations and Future Work

The study finds that the ISCG technology and economics look promising. However the analysis assumes a long-term, consistent syngas quality and quantity, which must be confirmed through site specific field demonstrations. A key limitation of the study is the reliance on ISCG technology vendor computer simulation results for design conditions significantly outside their operating experience:

- Deeper coal seams (> 200 m depth).

- Continuous operation at the claimed commercial scale syngas production rates.

It is therefore recommended that commercialization of the technology follow from field demonstration of ISCG technology by a consortium of interested parties to generate the required performance and scale-up data to support commercialization. This means:

- Investigating a strategy for commercialization of the ISCG technology as potentially a complementary, not primary, feedstock source for an existing commercial scale facility where the syngas can be gradually incorporated into the existing operations.

- Finalizing a strategy for field demonstration that stages promising ISCG technologies, outlines capital outlay, minimizes scale-up risk and maximizes scale-up data generation and results in an optimized ISCG module configuration for a specific site.

- Conducting targeted screening-level technical and regulatory work to define the requirements for a site-specific, scale-up and commercialization focused field demonstration of ISCG technology in Alberta.

- Evaluating additional options identified during the study (but not evaluated) for even more economically attractive flowsheet options for power generation.

- Developing a better understanding of ISCG technology through controlled laboratory physical test work coupled with advanced computer modelling.